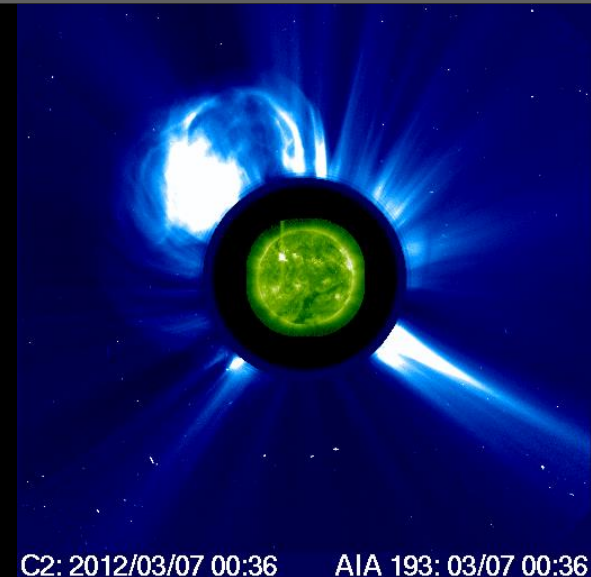
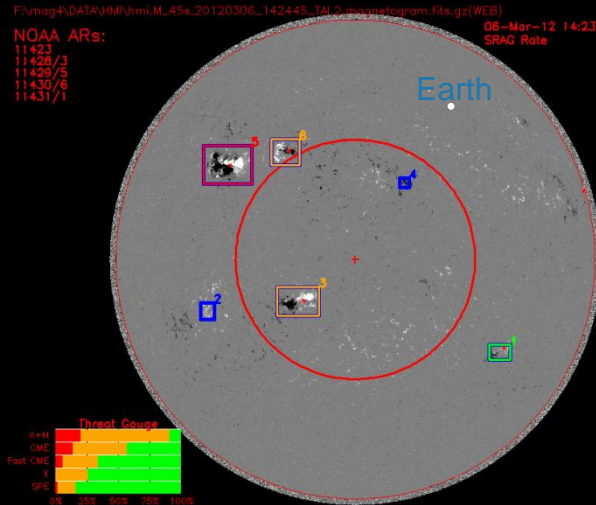


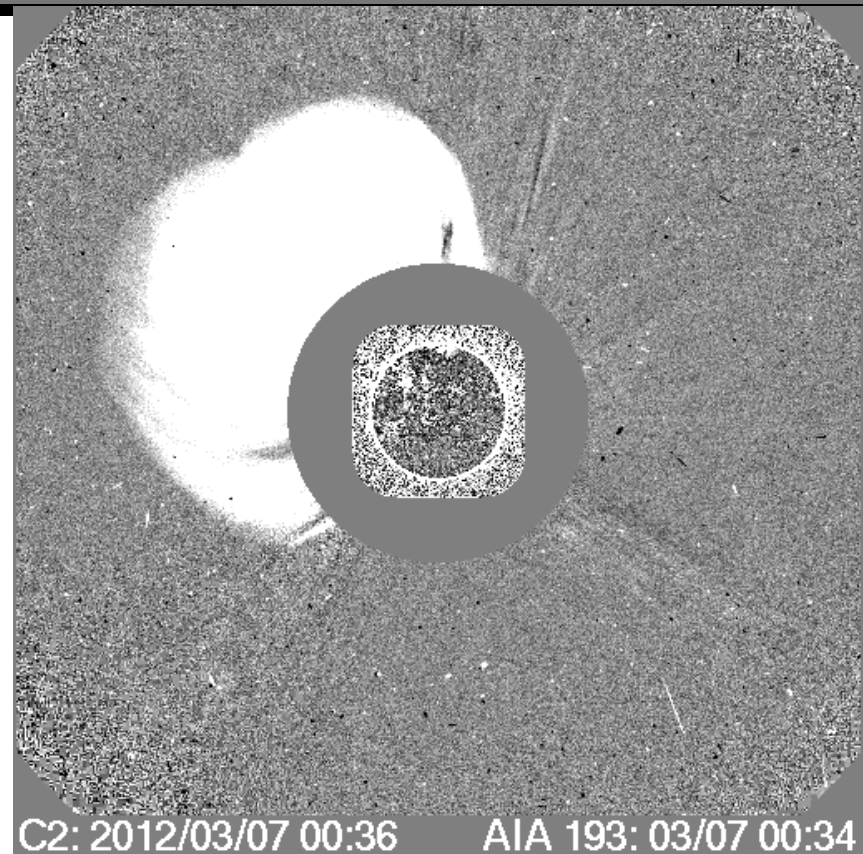
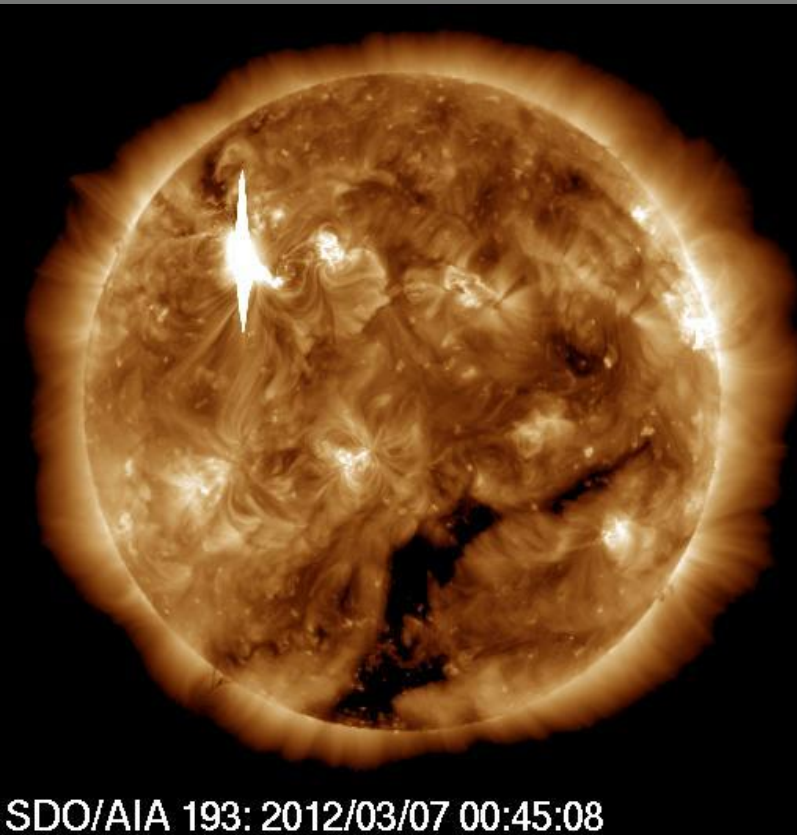


SCIENCE & TECHNOLOGY OFFICE



MAG4: An All-Clear Space-Weather Forecasting System

David Falconer (ZP13/UAH-CSPAR) & Nasser Barghouty (ZP12)
MSFC Innovation Day - November 1, 2016



- A major eruptive flare
 - the most powerful explosions in the solar system
 - dangerous to unshielded astronauts



- Space radiation mitigation was rated the highest priority technology for human spaceflight in NRC's 2012 report on NASA's technology roadmaps
- NASA lists **space radiation mitigation** as one of eight **core technology investments** in its *Space Strategic Technology Plan* (2013)
- NASA lists the following five specialty areas as **priority** areas for its space radiation mitigation core area:
 - monitoring*
 - detection*
 - forecasting*
 - risk assessment*
 - mitigation*

The ability to accurately forecast space-weather conditions and space-radiation levels is one of the highest (**level 3**) priorities on the agency's roadmap for ***Human Health, Life Support, and Habitation Systems*** (“TA 6.5.4”)



“Technology Area 6.5.4 Space Weather Prediction: The focus of this area is to advance improvements in solar particle event (SPE) forecasting and alert systems to minimize operational constraints for missions outside the protection of the Earth's geo-magnetic field.” <http://www.nasa.gov/offices/oct/home/roadmaps/index.html>



SPE is one of two major sources of highly-ionizing radiation levels facing human spaceflight in particular as well as space exploration in general

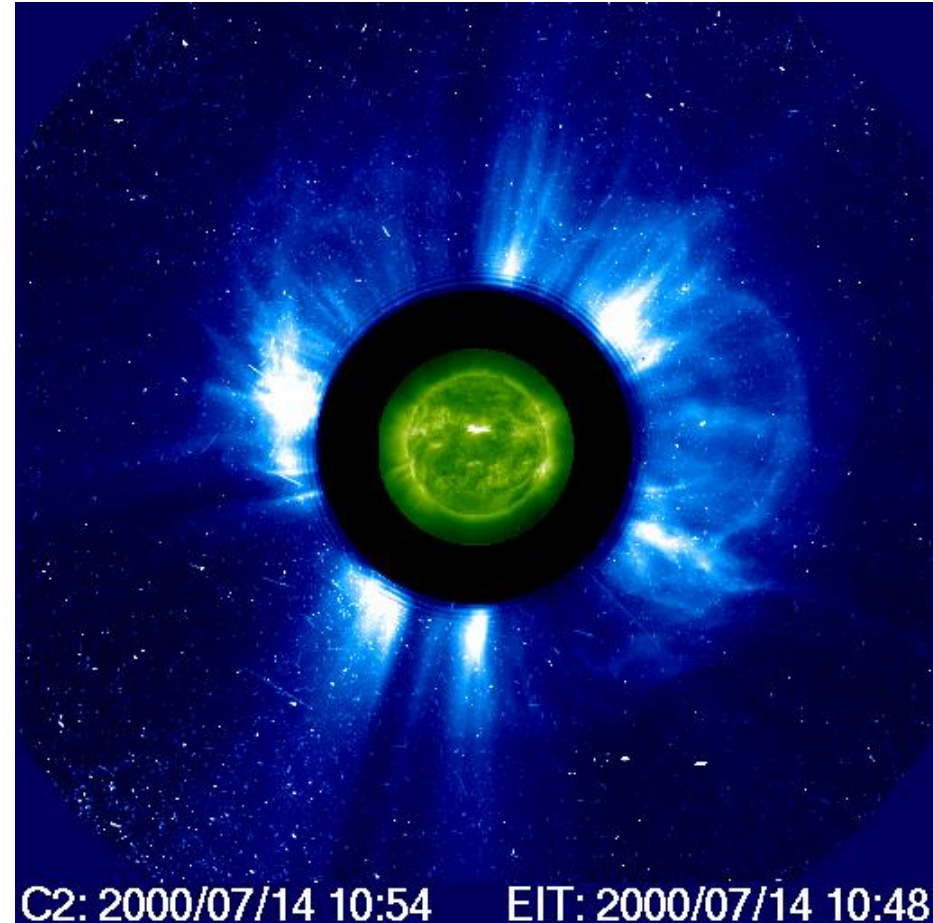


The technical challenges we face in understanding (and mitigating) these two sources are quite varied and complex...

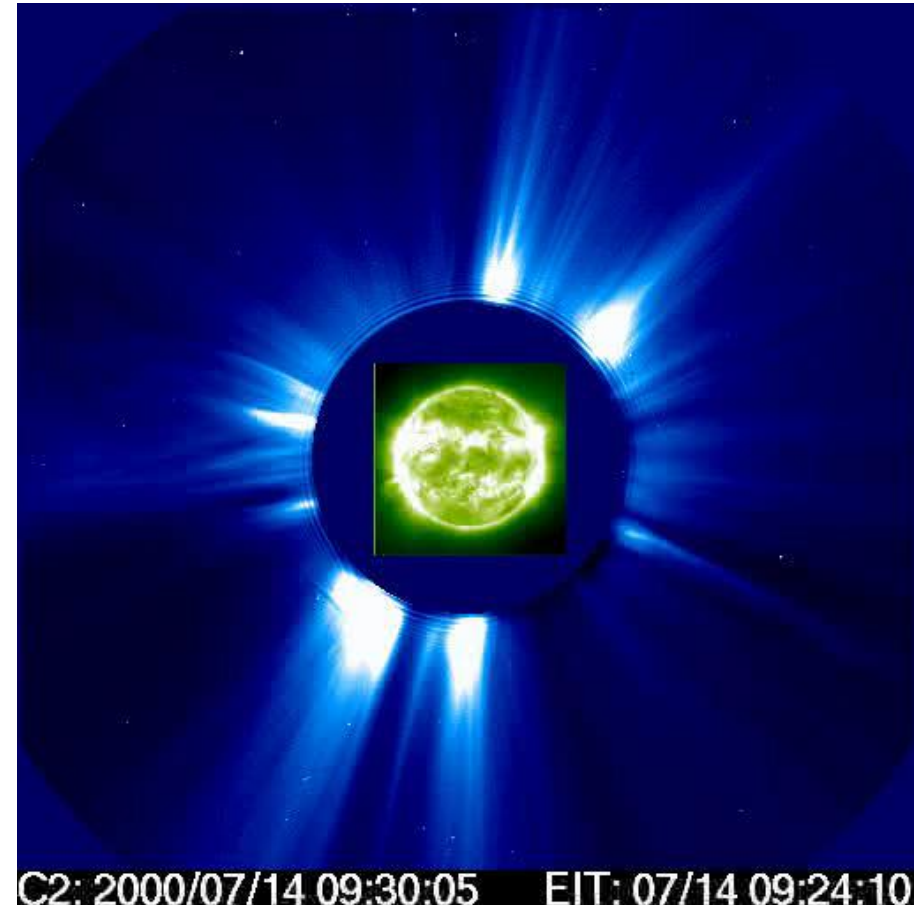


...and this is where MAG4 makes the difference!

- Eruptive flares can produce an SPE
- SPEs arrive 10 minutes to a day after the light of the flare
- For unshielded astronauts, SPEs can cause radiation damage and possibly lethal radiation doses



- Forecasting flares and CMEs is the first step to forecasting dangerous space weather
- SPEs are especially dangerous to astronauts especially during EVAs or away from LEO
- **One of the best forecasts is All Clear Forecasts**



Drivers of Space Weather

Flare

CME

SPE

ELECTROMAGNETIC RADIATION
(IMMEDIATE: TIME 8 MIN)

HIGH ENERGY PARTICLES
(DELAYED < HOUR)

ENHANCED SOLAR WIND
(DELAYED 1-3 Days)

X-EUV ULTRA-VIOLET VISIBLE LIGHT RADIO WAVES

ATOMIC NUCLEI

IONS AND ELECTRONS

SIMULTANEOUS EFFECTS

DELAYED EFFECTS

INCREASED D-LAYER
IONIZATION

OUTBURST OF
RADIO NOISE

ENHANCED
ENERGETIC
PARTICLES

IONIZATION

GEOMAGNETIC
STORM

GEOMAGNETIC
DISTURBANCE

RADIO
INTERFERENCE

**MANNED FLIGHT
RADIATION
HAZARD(I)**

ANOMALOUS
RADIO
PROPAGATION
RADAR
CLUTTER

IONOSPHERIC
STORM

ANOMALOUS
RADIO
PROPAGATION

SPACECRAFT
RADIATION
HAZARD (C³)

INDUCED
CURRENTS

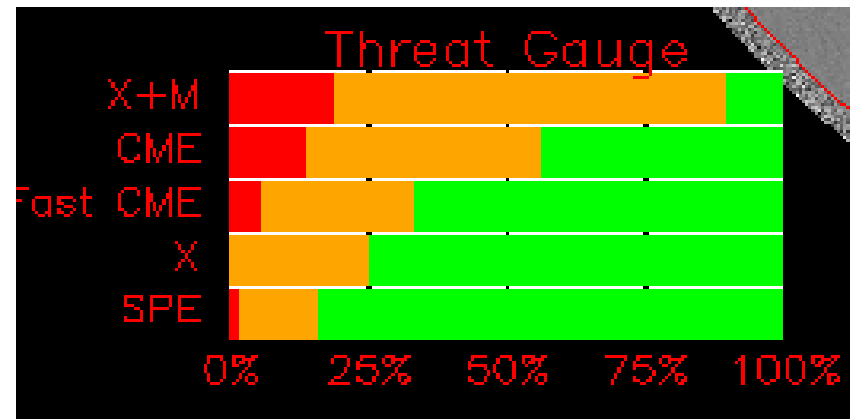
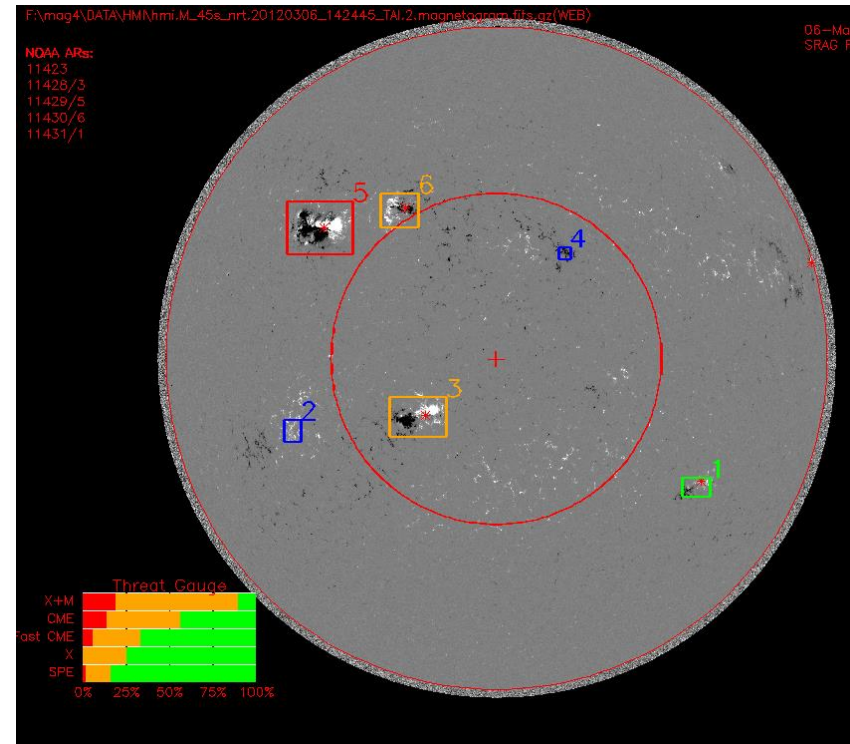
RADIO EFFECTS

SATELLITE DRAG

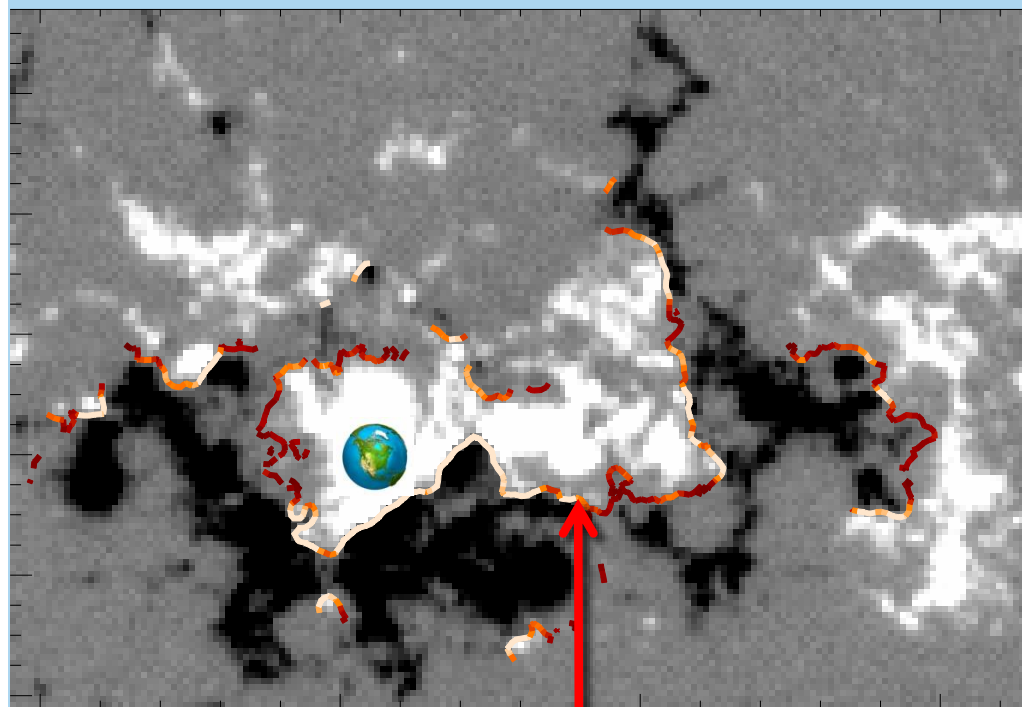
AURORA

Space Weather

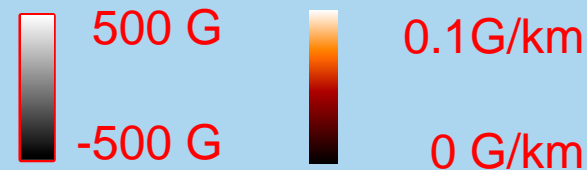
- Flares like earthquakes are very difficult to predict
- Historical records can provide empirical base forecasts
- MAG4 (Magnetogram Forecast) uses empirical data to predict the event rate of dangerous solar activity
- It does this automatically 24/7, making new forecasts every 96 minutes
- It forecasts **major flares**, coronal mass ejections (**CMEs**), and **SPEs**



- Flares and CMEs are powered by magnetic energy stored in the corona
- Direct measurements of coronal magnetic energy are inaccurate
- When the magnetic field is stressed, energy is stored and available for “explosive release”; more energy is stored, greater the chance of a major flare
- MAG4 uses a proxy to quantify the free energy stored in an active region
- Event rates are correlated with the magnitude of the free-magnetic-energy proxies
- **Data driven forecasts**

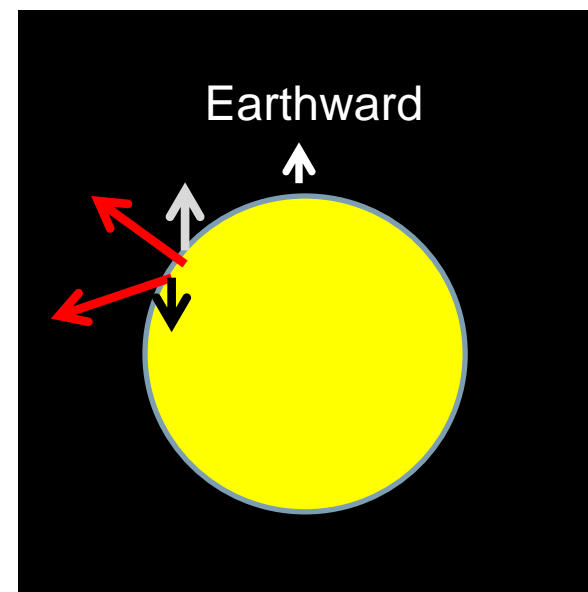


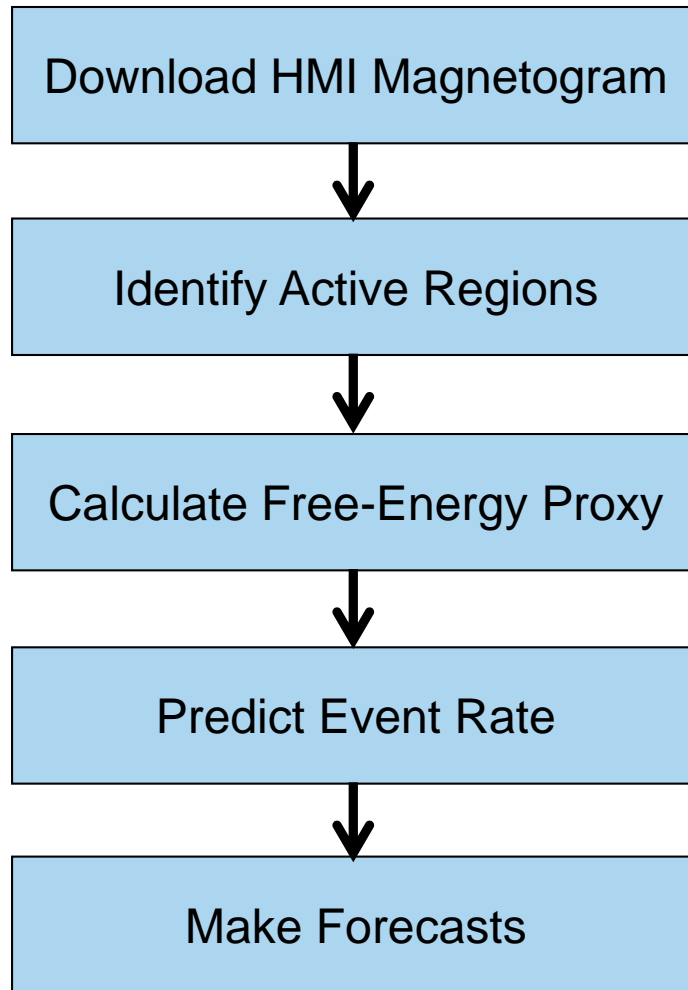
Neutral Line, color coded for gradient



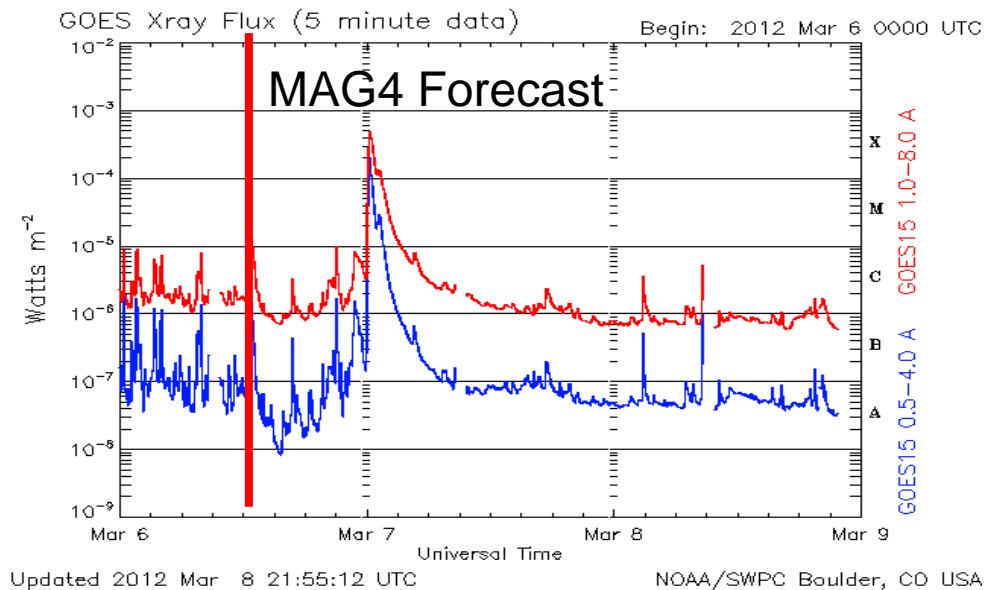
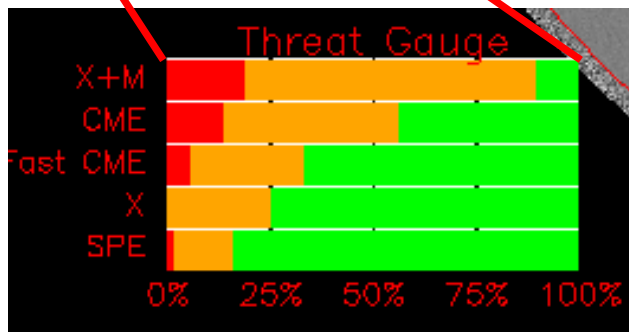
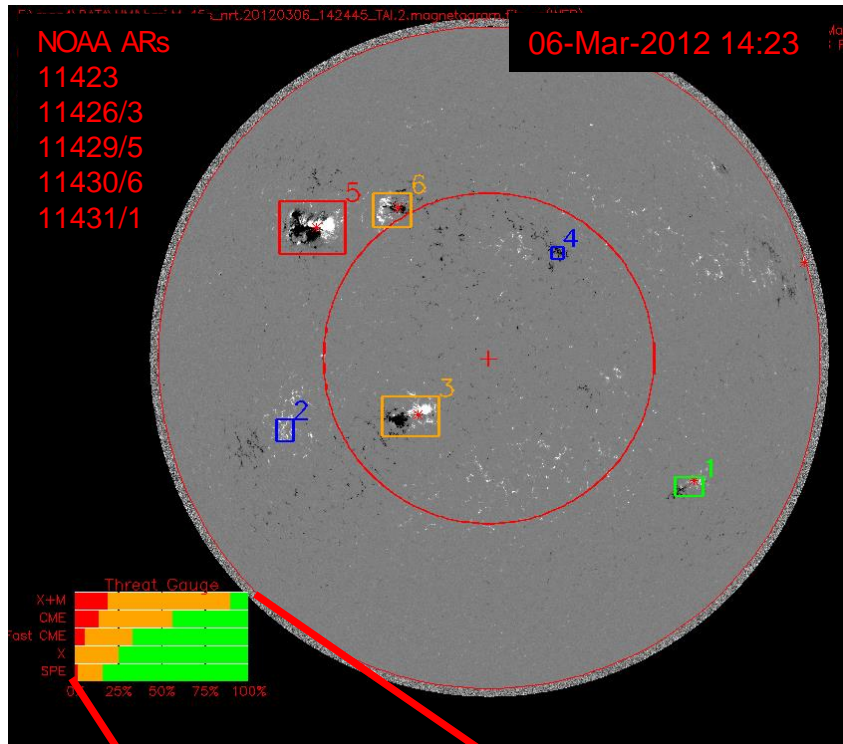
Earth magnetic field 1 G

1. Automatic data downloading
2. Identifying strong-magnetic field areas
3. Associating strong-magnetic field areas with NOAA active regions
4. De-projecting vector magnetograms
5. Neutral-Line free-energy proxy
6. Associating flares in near real time, for improved forecasts
7. gentle fails
8. missing or corrupted data
9. Customizing output for various customers



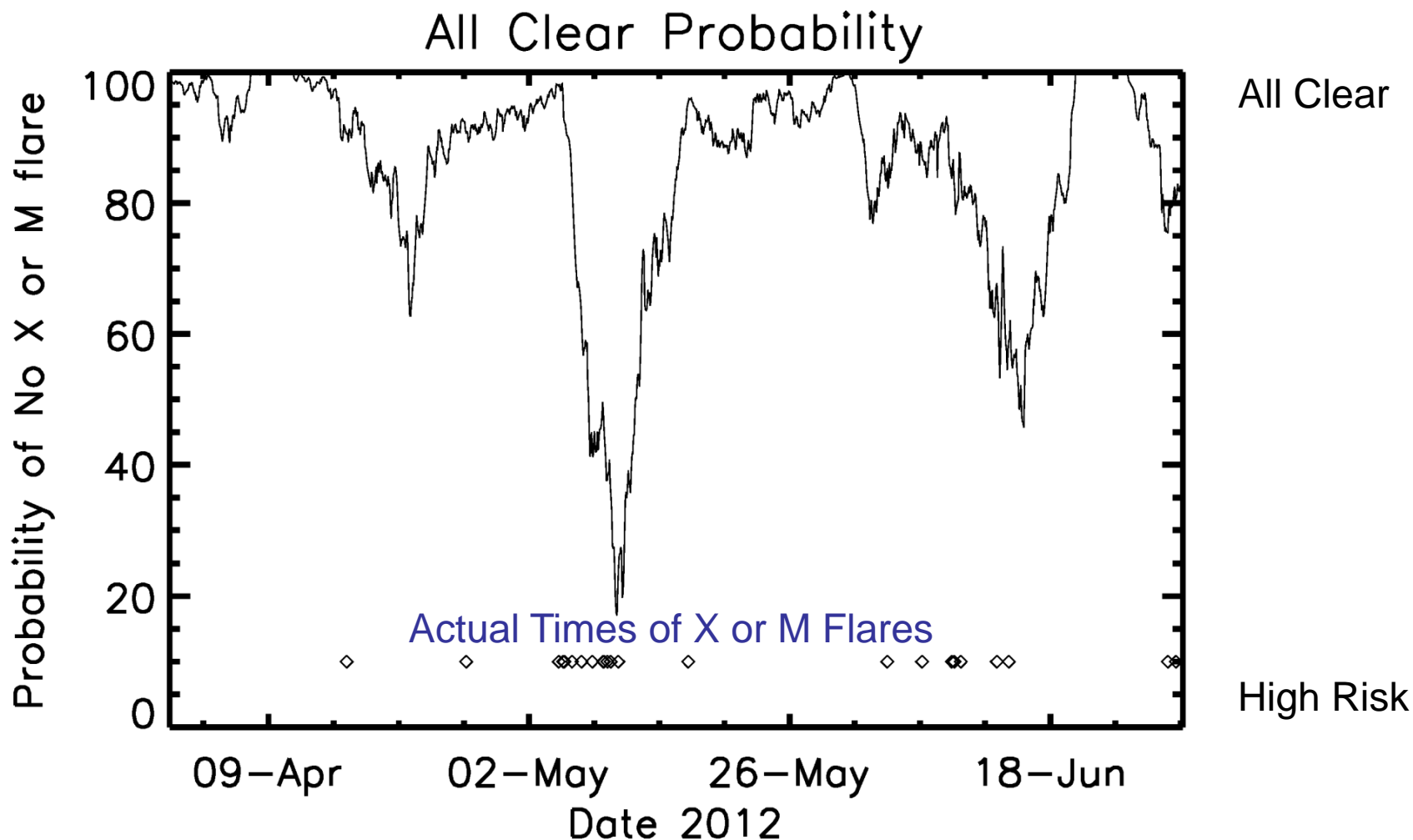


MAG4 is completely automated, from downloading magnetograms to outputting and storing forecast products



From NOAA's GOES satellite

Actual operational data from JSC/SRAG

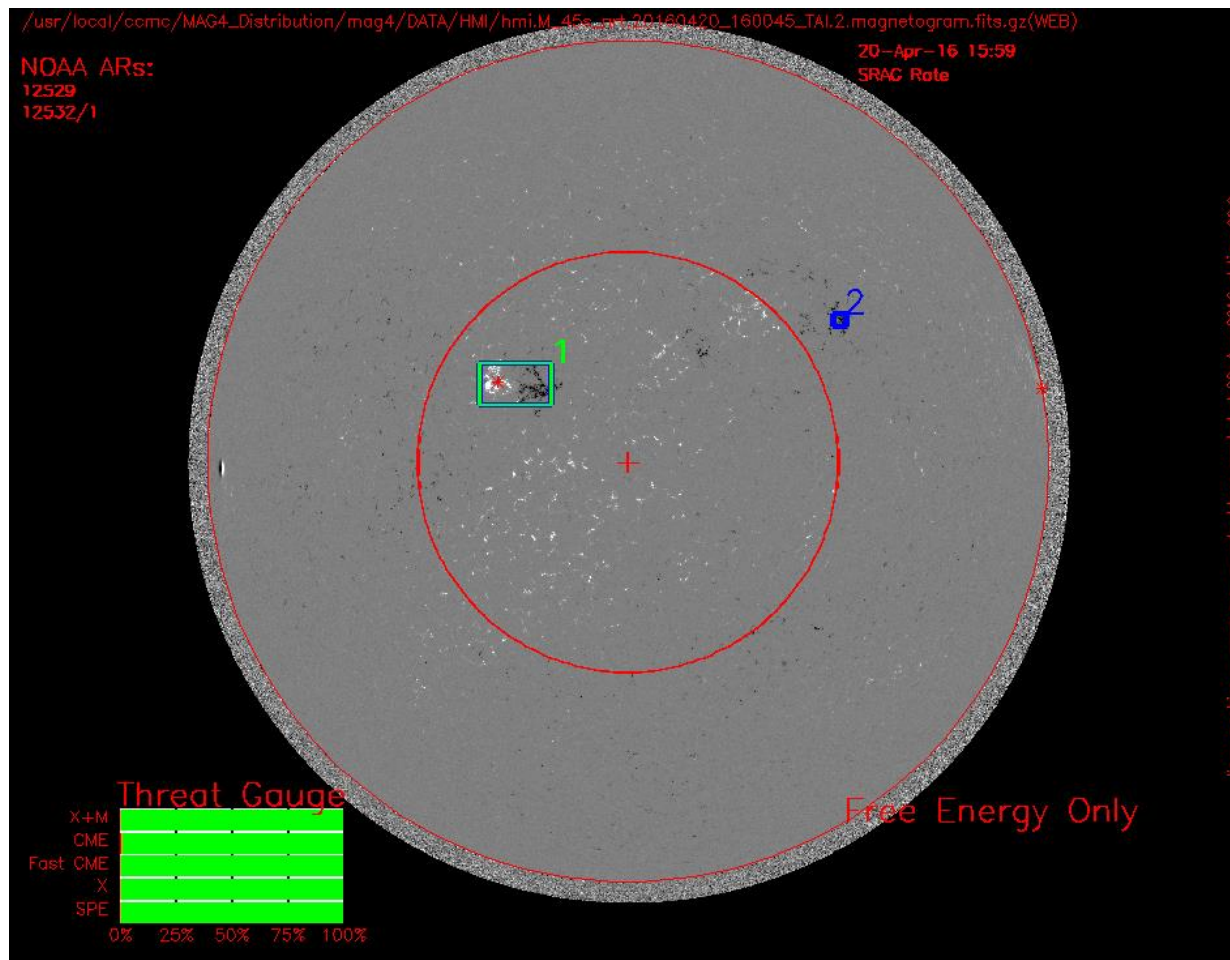


- ~~For rare events Percent of Correct (PC) forecast is of little use~~
- **Probability of Detection (POD)** events correctly forecasted
- **False Alarm Rates (FAR)** predicted events that did not occur

Forecast Method	POD	FAR
State of Art ¹	0.29	0.71
MAG4	0.38	0.48
Significance	(2σ)	(3σ)

¹ Input into NOAA Forecast

CCMC MAG4

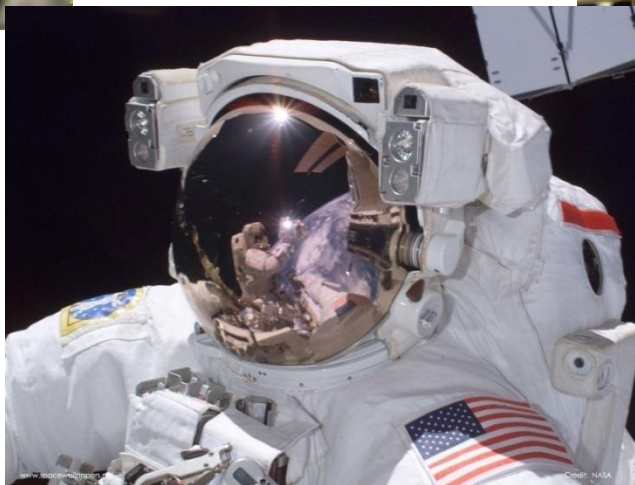




SRAG



EVA



Mission Control

- IDL was the language that was used for most of the development. IDL is good at array manipulation, and is the dominant language used for Solar Physics. There is an extension of IDL called SolarSoft, subroutines from there were copied and used, but since SolarSoft could be upgraded in a way that might cause problems, MAG4 is not run in the SolarSoft environment
- Java codes used as a backup tool for data retrieval at some point for a few months it was only way to get data
- PHP codes for communication with web
- A few Unix native programs fitted to be used in multi OS environment.(zip, wget, etc)

Platforms

We started with Windows, and Dr. Khazanov added other platforms as requested.

- SRAG JSC - Windows and Mac OS
- USAF - Linux and Windows
- CCMC - Linux

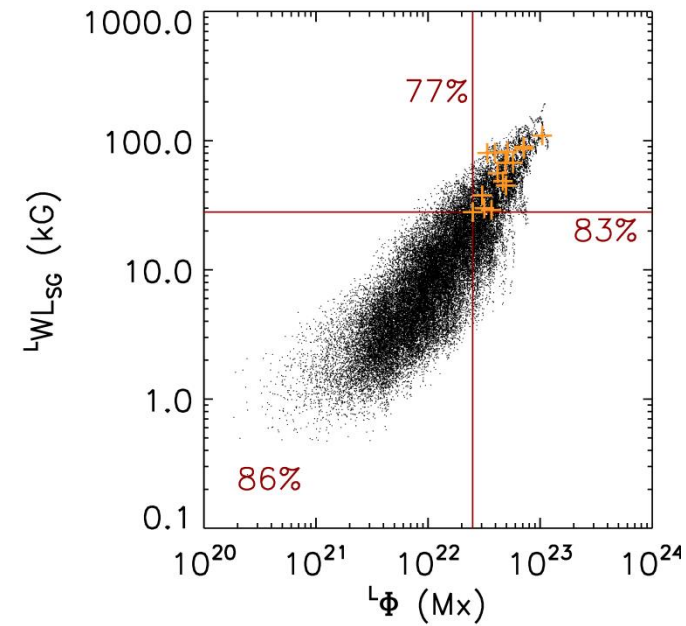
- **2011** MAG4 installed at JSC Space Radiation Analysis Group (SRAG) as a NRT (Near-Real-Time) forecasting tool, and SRAG began pre-operations testing
- **2012** Provided NOAA web access to MAG4 NRT forecasts
- **2013** MAG4 upgraded so that it can use a combination of **free-energy proxy** and previous **flare activity**, for **better accuracy**
- **2013** Won the Silver Snoopy Award
- **2015** Transition from HMI line-of-sight magnetogram to vector magnetograms



Silver Snoopy

“Employees must have significantly contributed to the human space flight program to ensure flight safety and mission success.”

- Continue to afford support and upgrades to JSC/SRAG
- Correct for known projection errors in free-energy proxies
- Take full advantage of vector magnetograms
- Improve All Clear Forecast for SPE
- Partner with Air Force, and NOAA



The gold crosses represent active regions that produce an SPE while the black dots do not.

- Magnetograms are spatial maps of the magnetic field strengths
- They come in two basic types
 - line-of-sight (right)
 - vector magnetograms
- Free-energy proxies can be measured for Active Regions (areas with sunspots) from either type of magnetogram
- Line-of-sight magnetograms suffer reduced accuracy further from disk center

Magnetograms & identify active regions

NOAA ARs
11423
11426/3
11429/5
11430/6
11431/1

06-Mar-2012 14:23

NOAA
Active
Regions
(ARs)

Best
Accuracy

A full-disk line-of-sight magnetogram of the Sun, from SDO/HMI.

2. Skill Metrics Significance of Upgrade

Forecast Method	YY	YN	NY	NN	PC(%)	POD	FAR	HSS	TSS
McIntosh/NOAA	259	638	631	18476	93.7	0.29	0.71	0.26	0.26
Free-Energy Proxy Present MAG4	273	284	618	18830	95.5	0.31	0.50	0.35	0.47
Free-energy proxy and previous flare activity Upgraded MAG4	340	317	551	18797	95.7	0.38	0.48	0.42	0.49
Best	890	0	0	1911 4	100	1	0	1	1

Improvement in Metric	PC(%)	POD	FAR	HSS	TSS
McIntosh/NOAA Present MAG4	1.8±0.5 (4σ)	0.03±0.05 (0.3σ)	0.21±0.07 (3σ)	0.10±0.04 (2σ)	0.21±0.07 (3σ)
Present MAG4 Upgraded MAG4	0.2±0.2 (0.7σ)	0.08±0.03 (2σ)	0.02±0.05 (0.5σ)	0.06±0.03 (2σ)	0.03±0.05 (0.5σ)

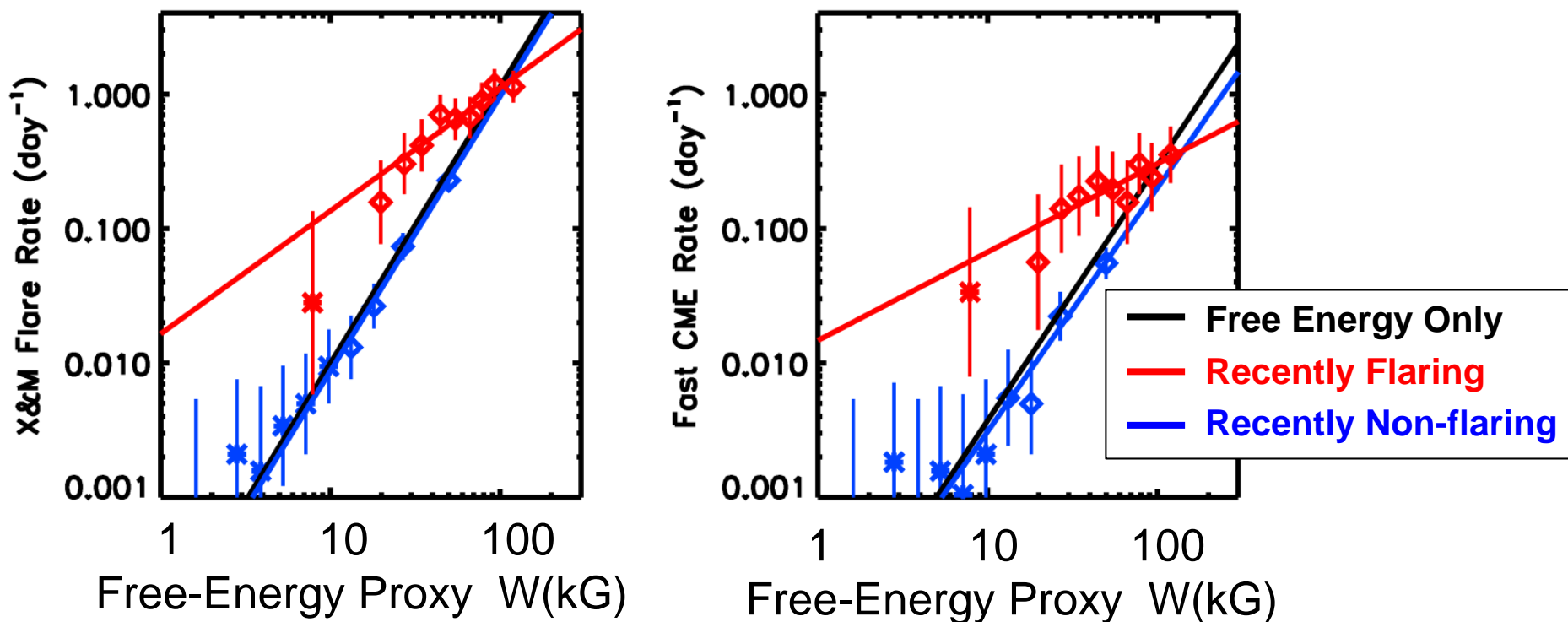
2. Skill Metrics Equations

	Actual Yes	Actual No
Predict Yes	YY	YN
Predict No	NY	NN

Metric Equations

Percent Correct	$PC = (YY + NN) / (YY + YN + NY + YY)$
Probability of Detection	$POD = YY / (YY + NY)$
False Alarm Rate	$FAR = YN / (YY + YN)$
Heidke Skill Score	$HSS = 2 * (YY * NN - YN * NY) / [(YY + NY) * (NY + NN) + (YY + YN) * (YN + NN)]$
True Skill Score	$TSS = (YY * NN - NY * YN) / ((YY + NY) * (YN + NN))$

1. Recent Flare History (In Progress)

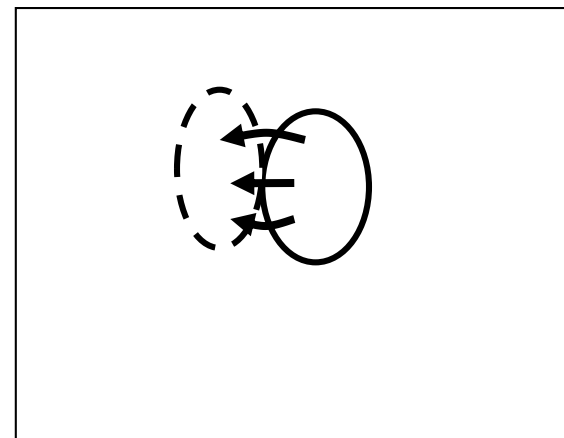
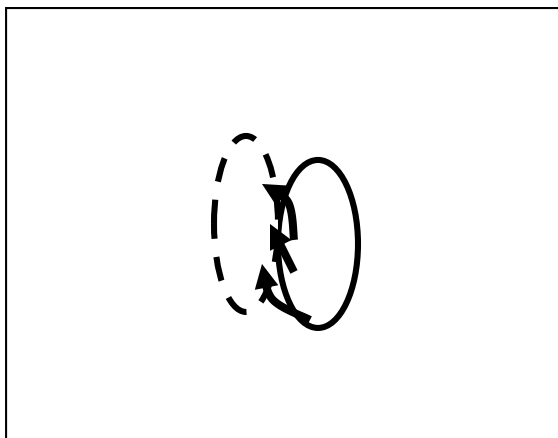
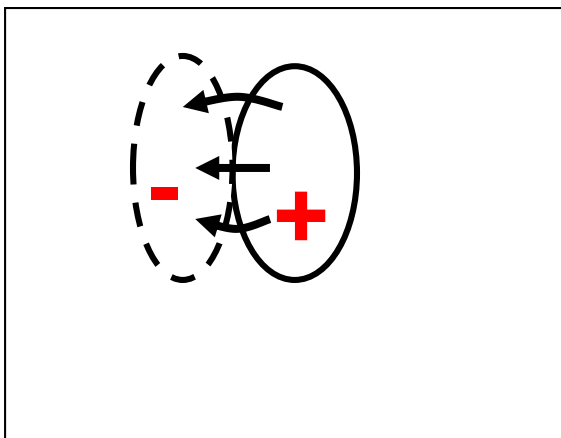


Active regions that have recently produced an X- or M-Class flare are more likely to produce flares in the near future

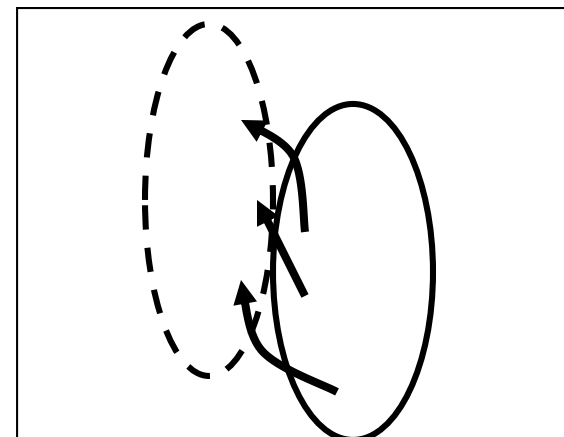
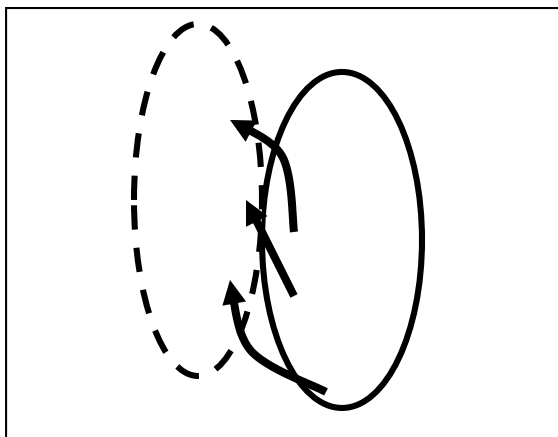
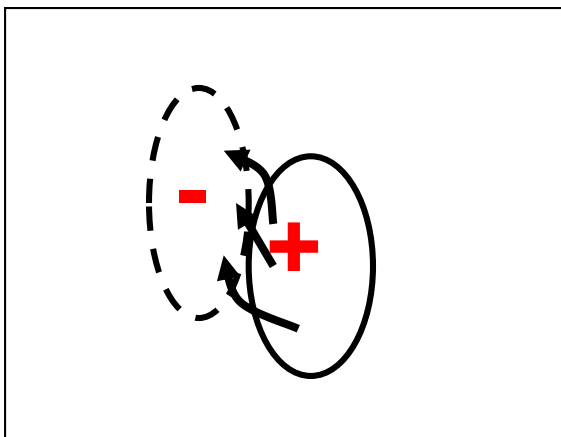
Contours Vertical Magnetic Field
Arrows Transverse Magnetic Field

Currents $\sim 10^{12}$ Amps

Less



More



Twist

Size

**Free Magnetic Energy
Or Nonpotentiality**

June 26, 2013

C1, C1.5 flares

March 7, 2012

X5.4, X1.3, C1.6

CME 2684, 1825 km/sec,

Solar Energetic Proton Event reaches
6530 particle flux unit >10MeV

